



Generic calibration procedures for nacelle-based profiling lidars

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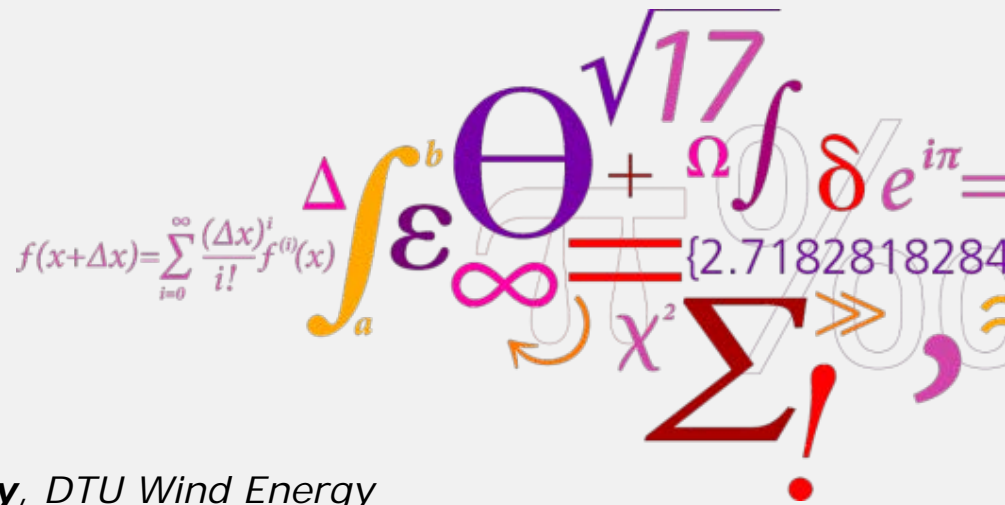
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Generic calibration procedures for nacelle-based profiling lidars

Concept, setup and results

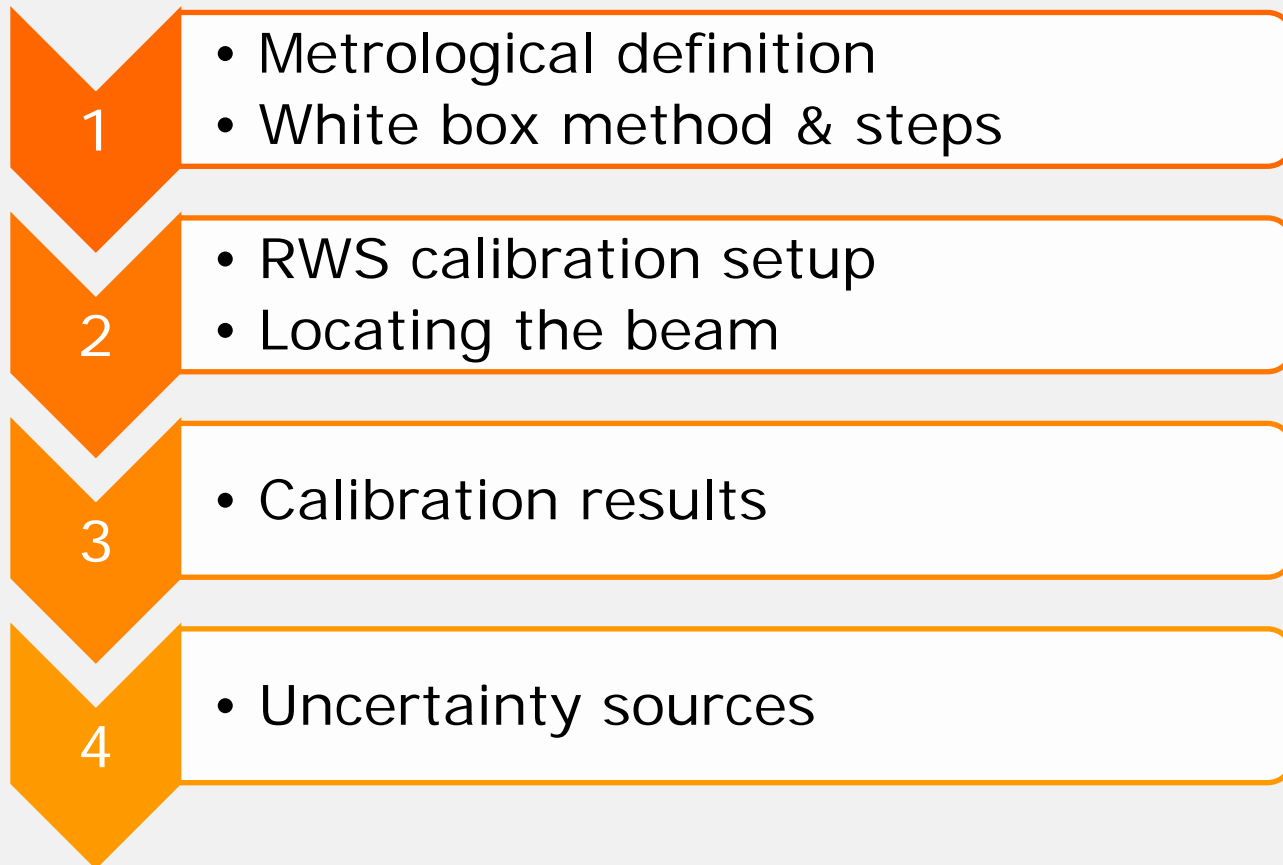
5-beam Demonstrator
(Avent Lidar Technology)

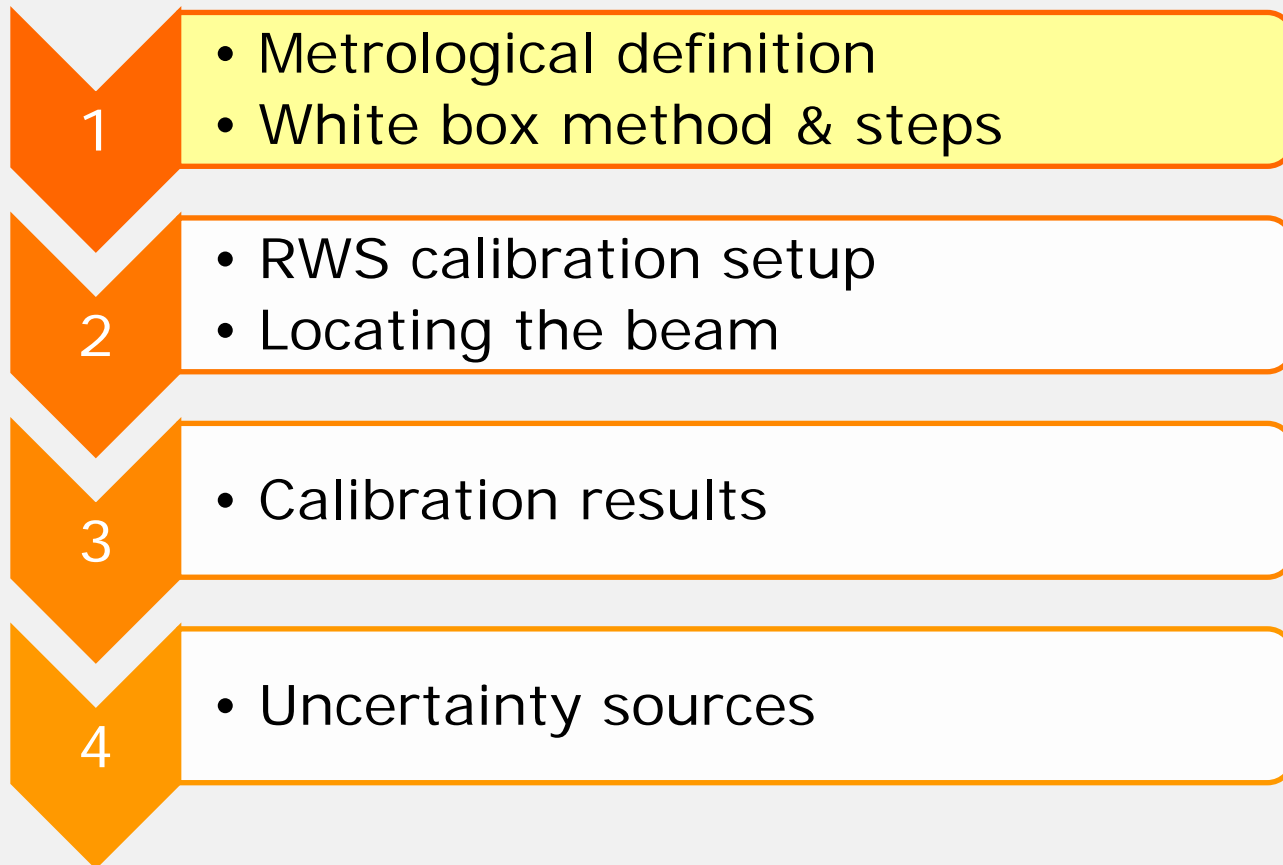
ZephIR Dual Mode
(ZDM, ZephIR lidar)


$$f(x+\Delta x) = \sum_{i=0}^{\infty} \frac{(\Delta x)^i}{i!} f^{(i)}(x)$$
$$\int_a^b \epsilon \Theta^{\sqrt{17}} + \Omega \int \delta e^{i\pi} = \{2.7182818284\}$$
$$\chi^2 \sum!$$

A. Borraccino, R. Wagner, M. Courtney, DTU Wind Energy

Outline





What is meant by calibration?

Let's speak the same metrological language !!



- **VIM (cf. JCGM 200:2012)**

<http://www.bipm.org/fr/publications/guides/vim.html>

operation that, under specified conditions, in a first step, establishes a relation between the **quantity values** – i.e. the **reference** – with **measurement uncertainties** provided by measurement standards and corresponding **indications** – i.e. **measurand to calibrate** – with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a **measurement result** from an indication.

NOT CLEAR?

- **Reformulation in 3-step process**

1. **Relation:** measurand = f(reference)

2. **Uncertainties on measurand**

= uncertainties on reference + measurements uncertainties

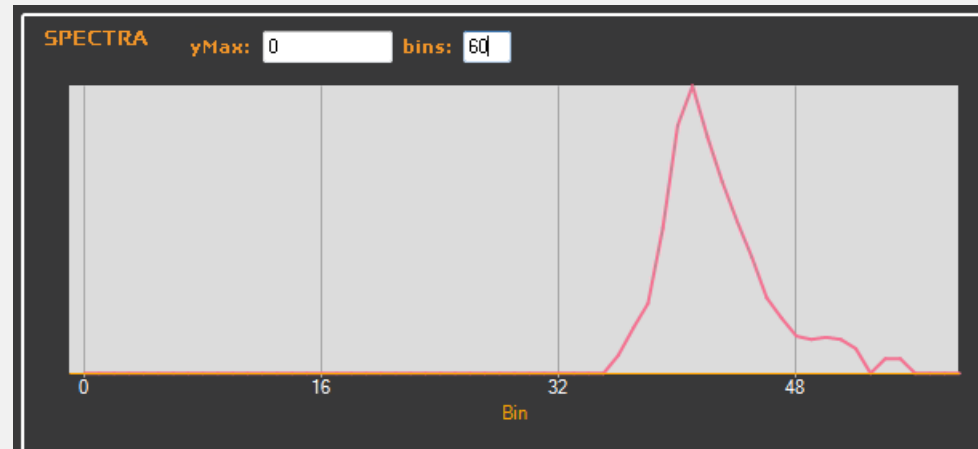
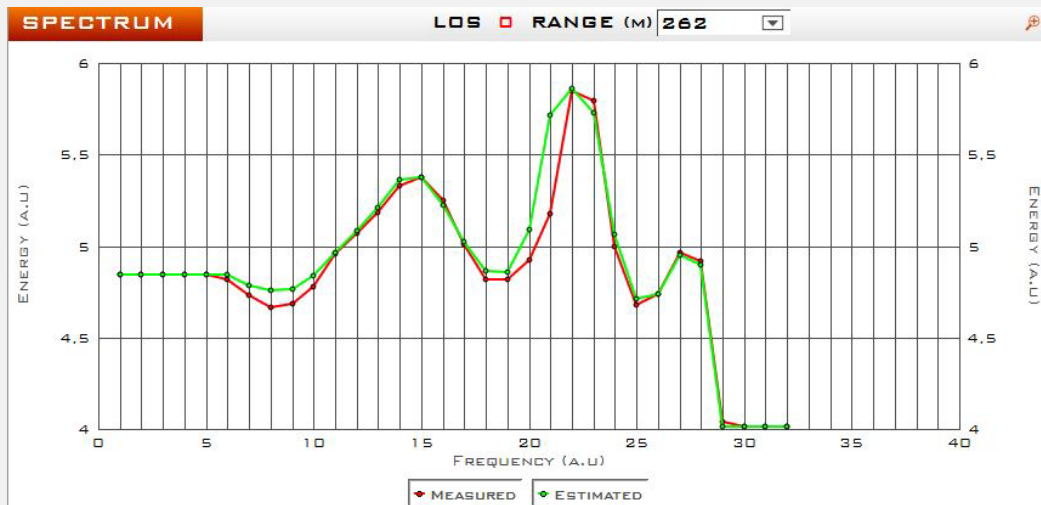
3. Use calibration relation = apply a correction on measurand

➔ ensures link in measurement chain and **traceability**



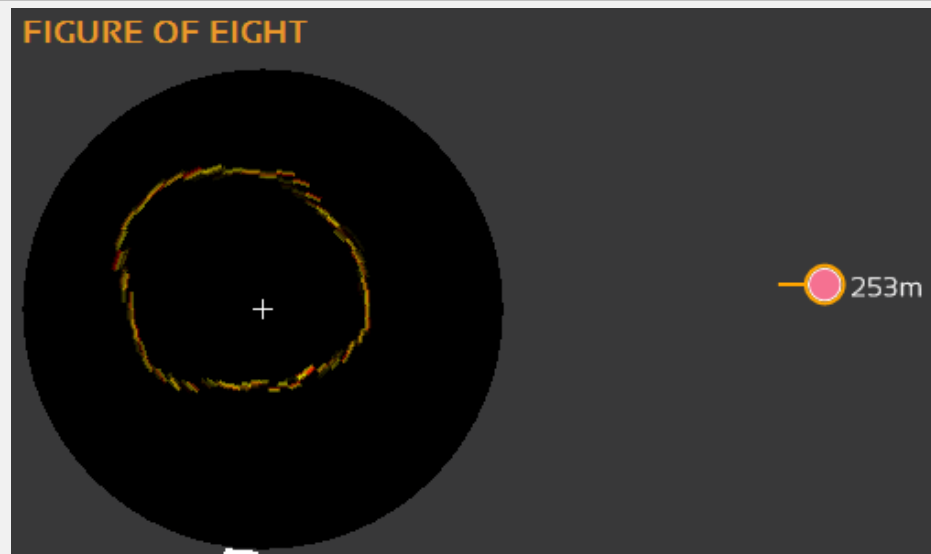
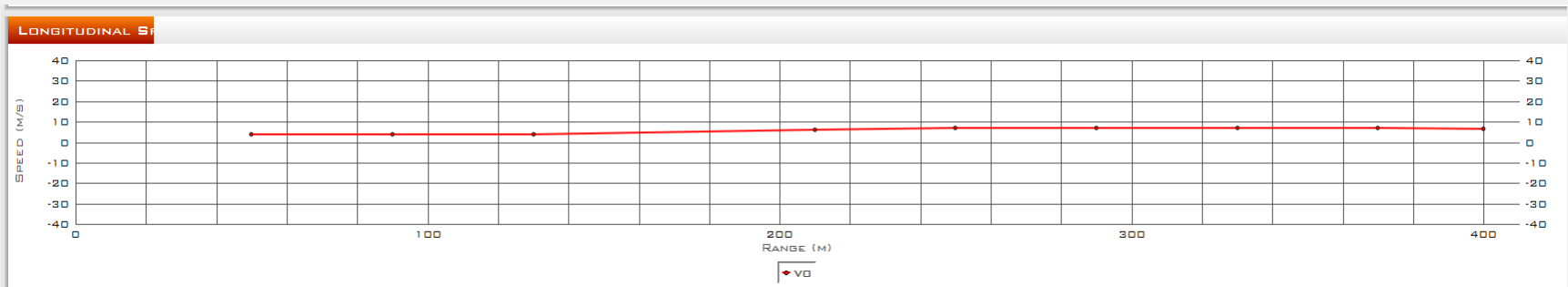
White box principles

- 3 levels of measurands in a lidar
 - Raw Doppler spectra



White box principles

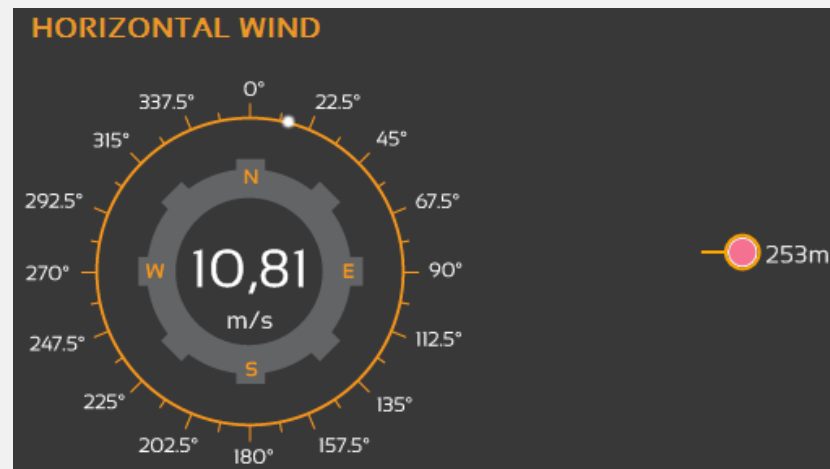
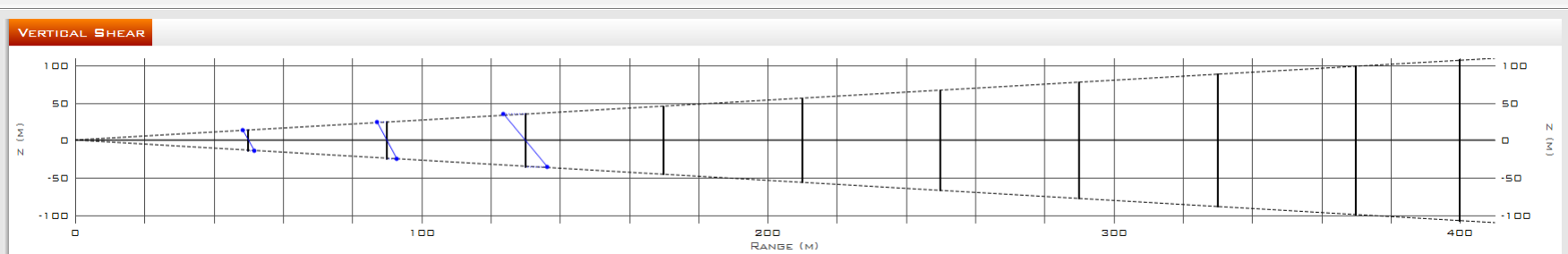
- **3 levels of measurands in a lidar**
 - Raw spectra
 - Radial wind speed (RWS) or Line-of-sight velocity





White box principles

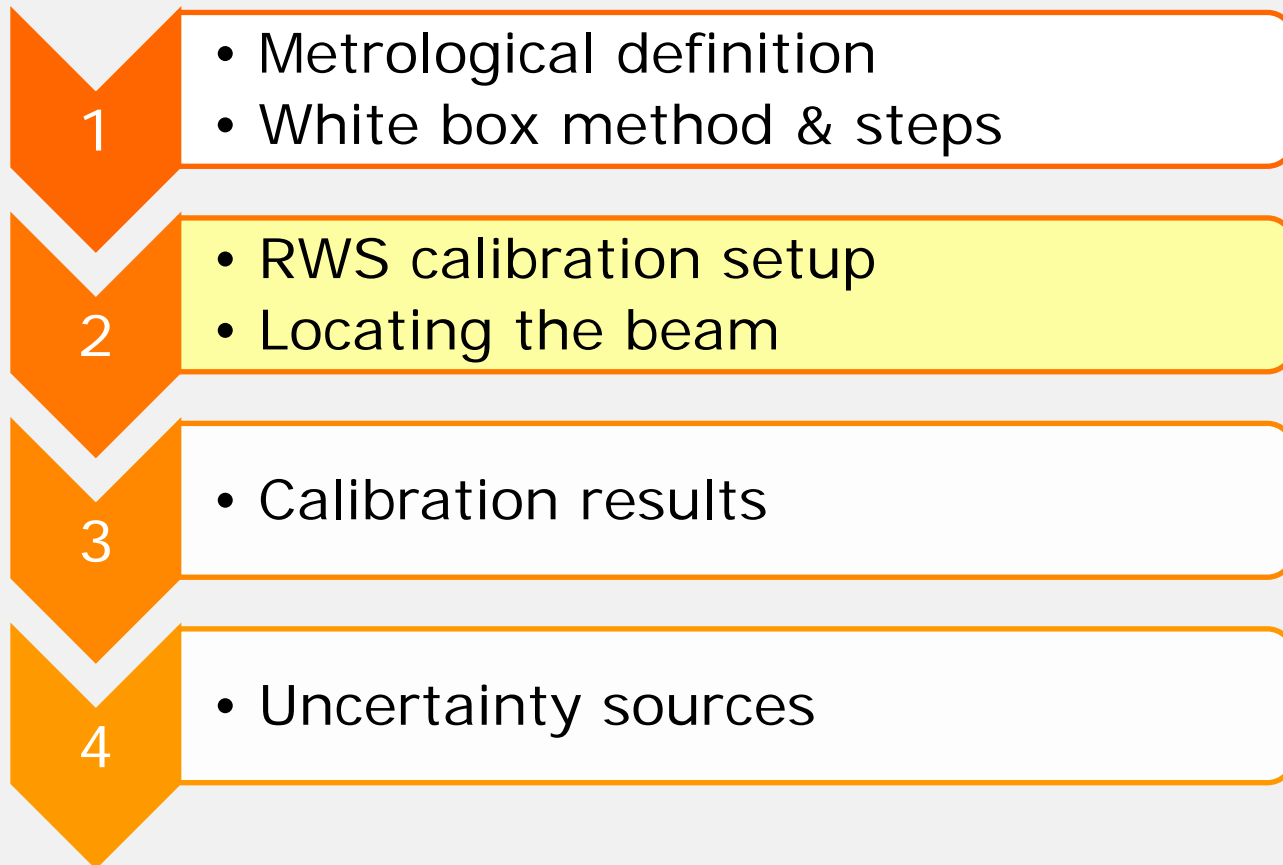
- **3 levels of measurands in a lidar**

- Raw spectra
- Radial wind speed or Line-of-sight velocity
- **Reconstructed parameters:** wind speed & direction, shear (horizontal, vertical, longitudinal), veer, turbulence

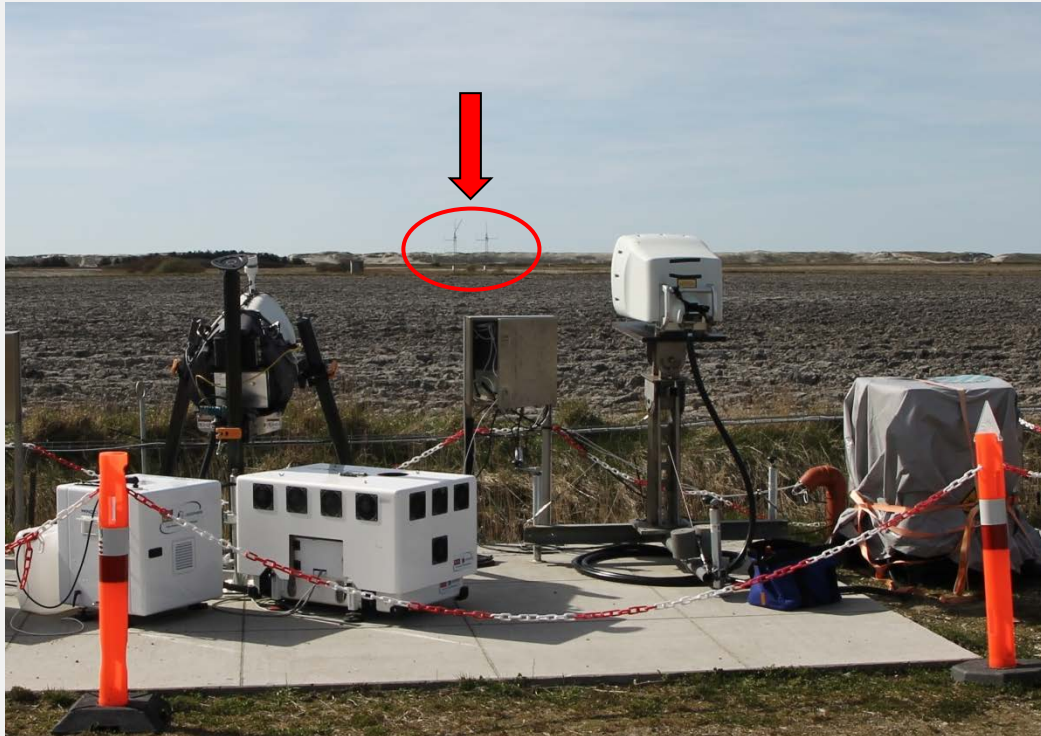


White box principles

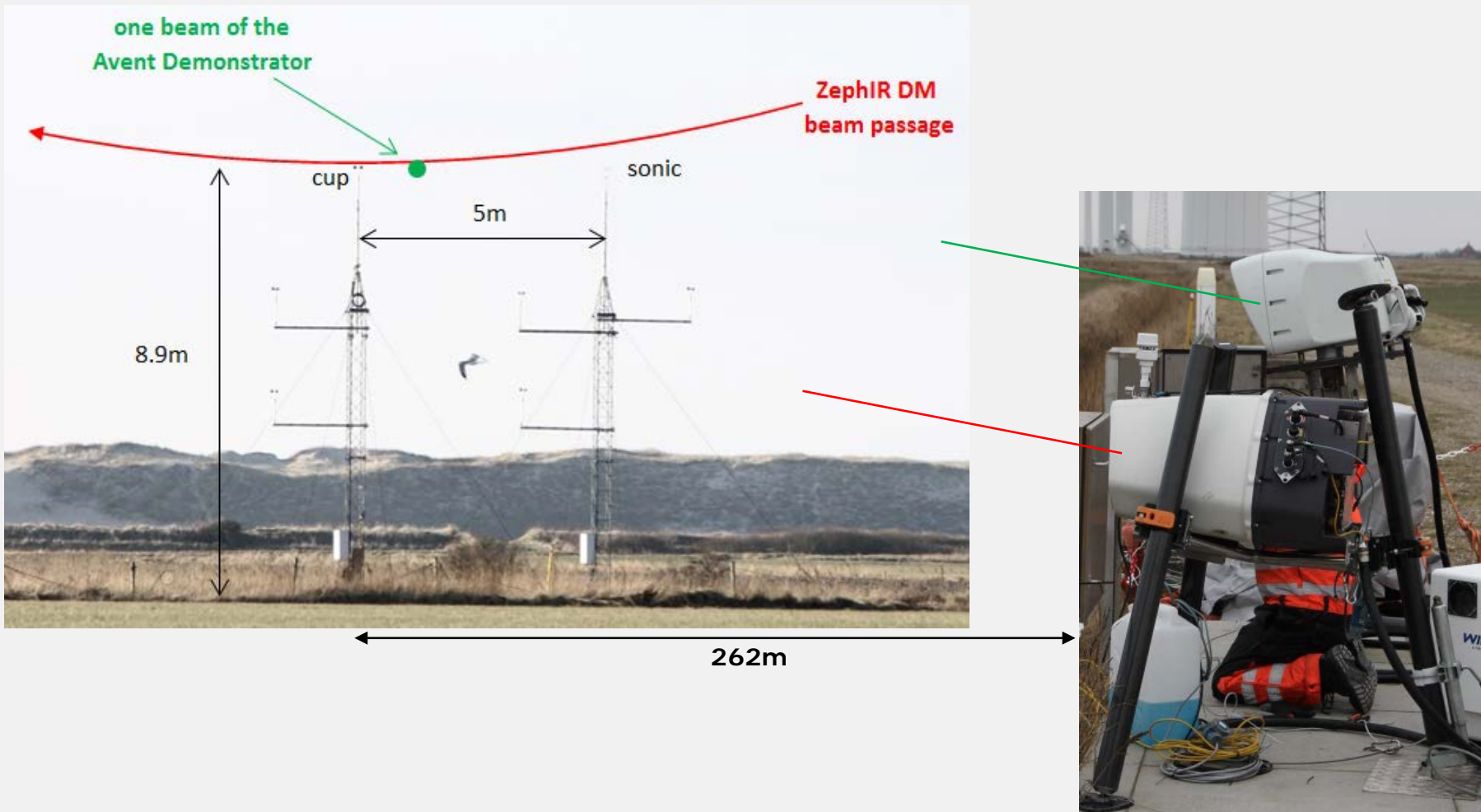
- Black box: calibration of reconstructed parameters 
- White box: calibration of reconstruction algorithms' inputs 
 - 1) Geometry of the lidar: where is the beam?
 - a. Inclinator calibration
 - b. Opening / cone angles check
 - 2) Position the beam close to a reference instrument
 - 3) Calibrate RWS by comparing to reference
 - 4) Derive uncertainties: reference → RWS
 - 5) Combine RWS according to reconstruction algorithms
 - 6) Derive uncertainties on ANY reconstructed parameter
 - as long as the algorithm is known
 - and correlation between the parameters



RWS calibration setup

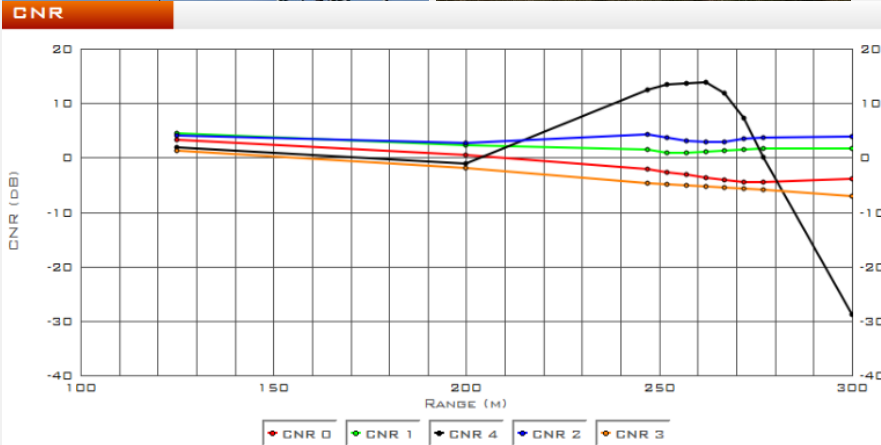


RWS calibration setup



Locating the beam

Avent Demonstrator

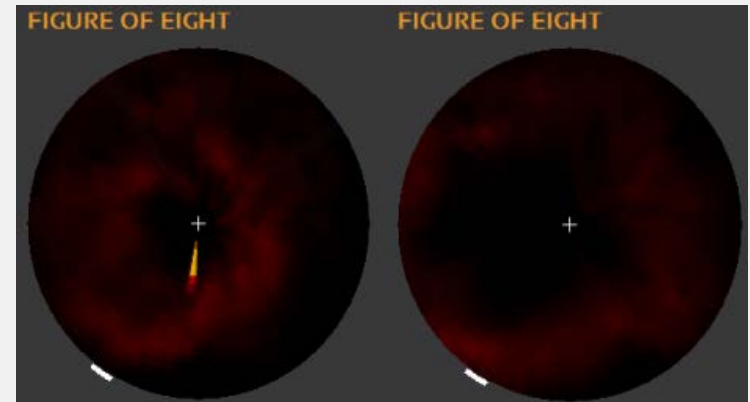


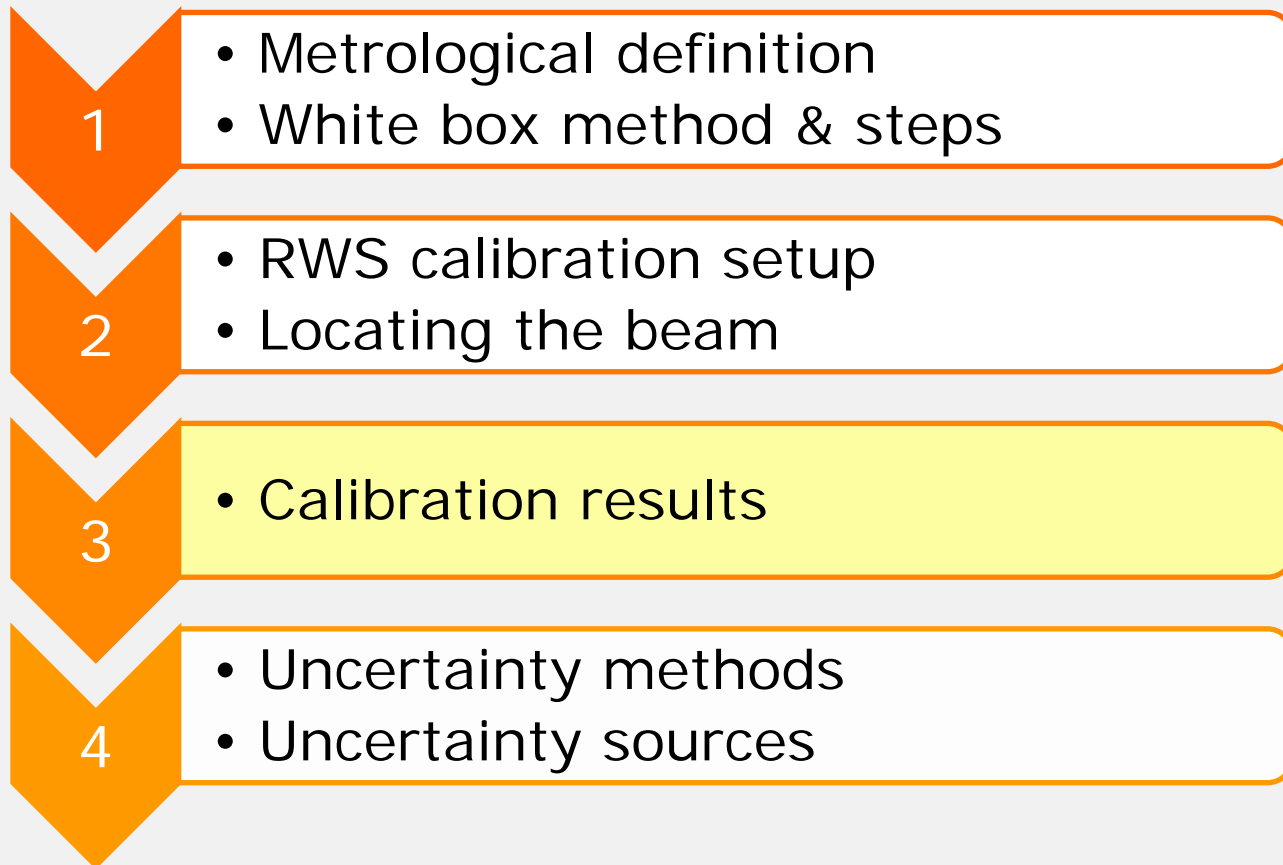
Zephir Dual Mode

- adjust the tilting progressively



- Hit a moving target (e.g. cups)





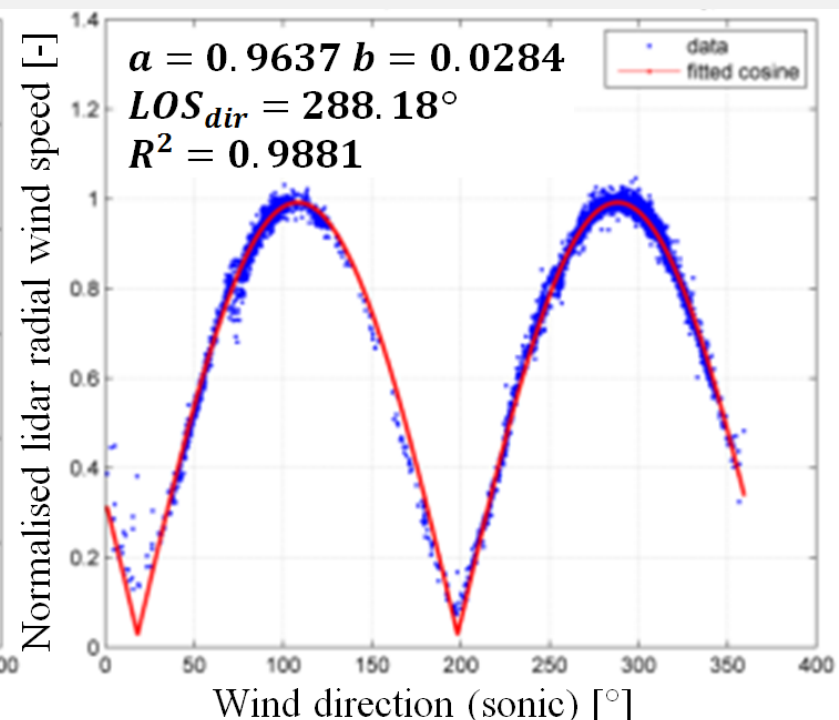
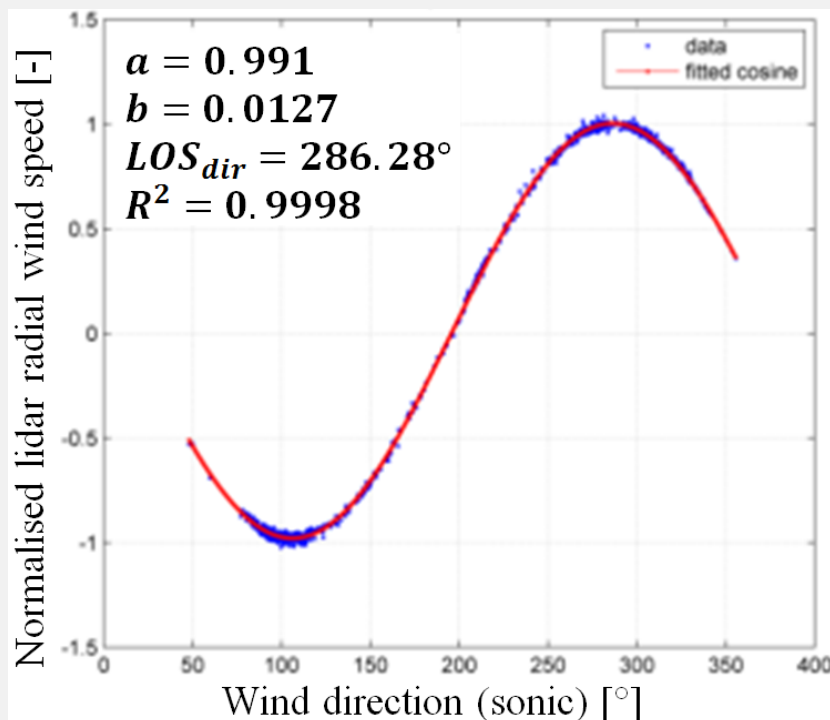
Data analysis (Avent: L, Zephyr: R)

• Main data

$$Ref_{eq\ RWS} = HWS \cdot \cos(\text{tilt}) \cdot \cos(WD - LOS_{dir})$$

- Cup: horizontal wind speed
- Sonic: wind dir
- Lidar: LOS velocity + inclination

• LOS direction evaluation 1: cosine / rectified cosine fitting



Data analysis (Avent: L, Zephir: R)

• LOS direction evaluation 2 (finer)

– Projection angle range: LOS dir (V1) $\pm 1^\circ$

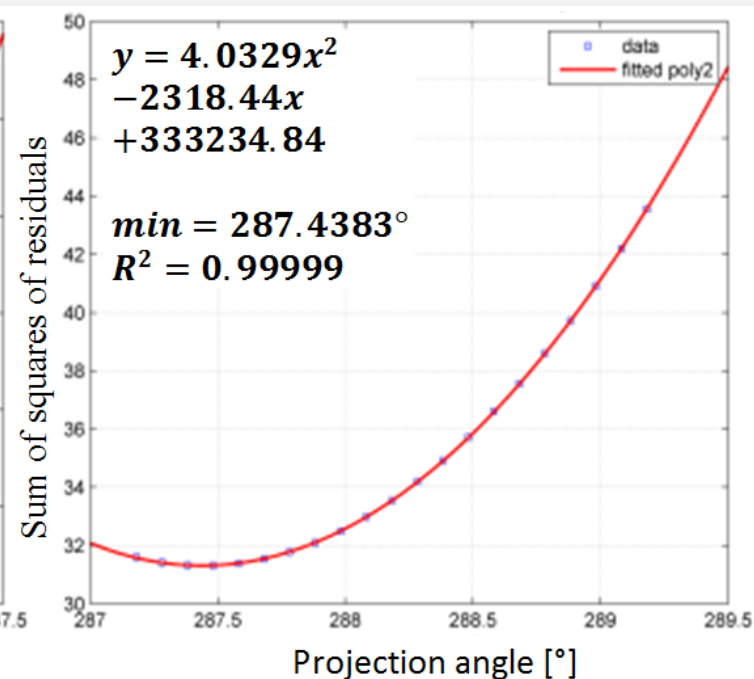
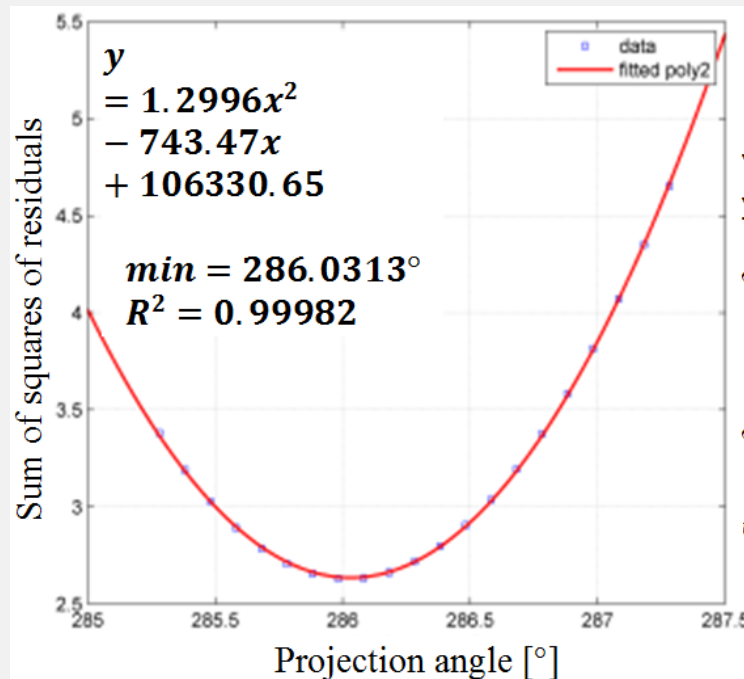
– Linear reg. each 0.1°

$$y = RWS$$

$$x = HWS \cdot \cos(WD - \text{proj angle}) \cdot \cos(\text{physical beam inclination})$$

$$y = a \cdot x + b \rightarrow 1 \text{ RSS value}$$

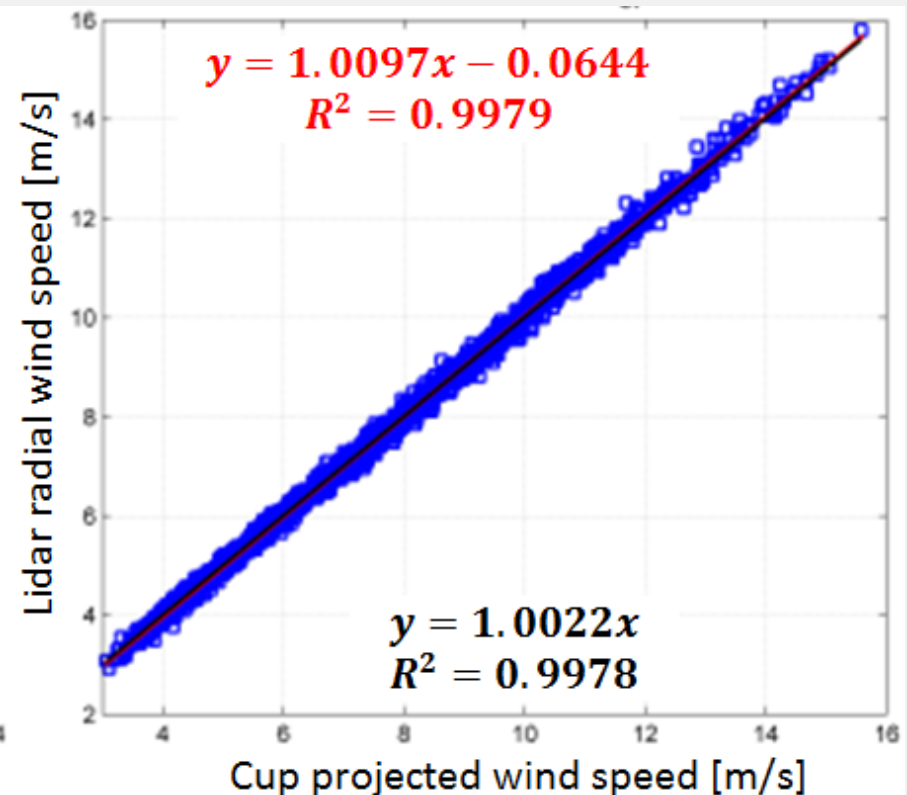
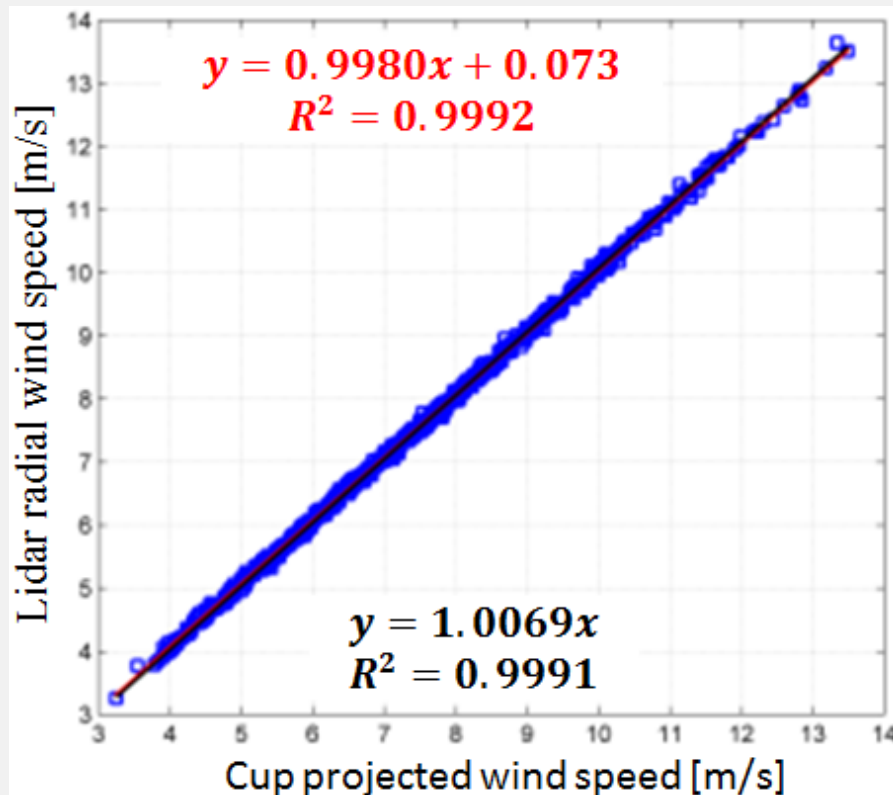
– LOS dir = min parabola



Calibration results (Avent: L, Zephyr: R)

- "RAW" calibration results

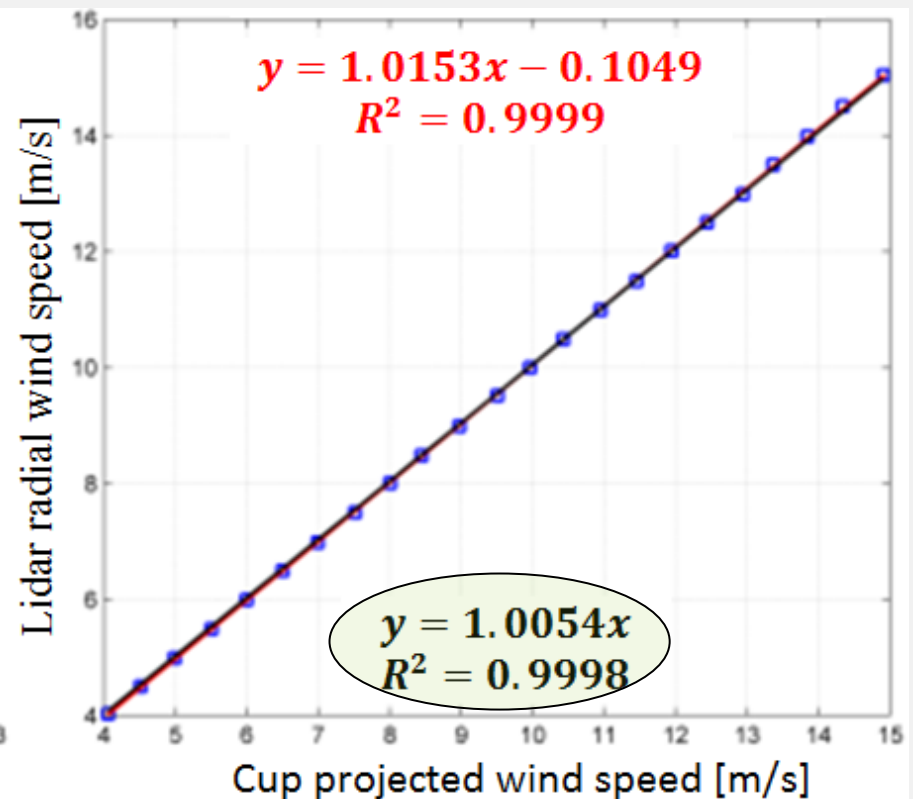
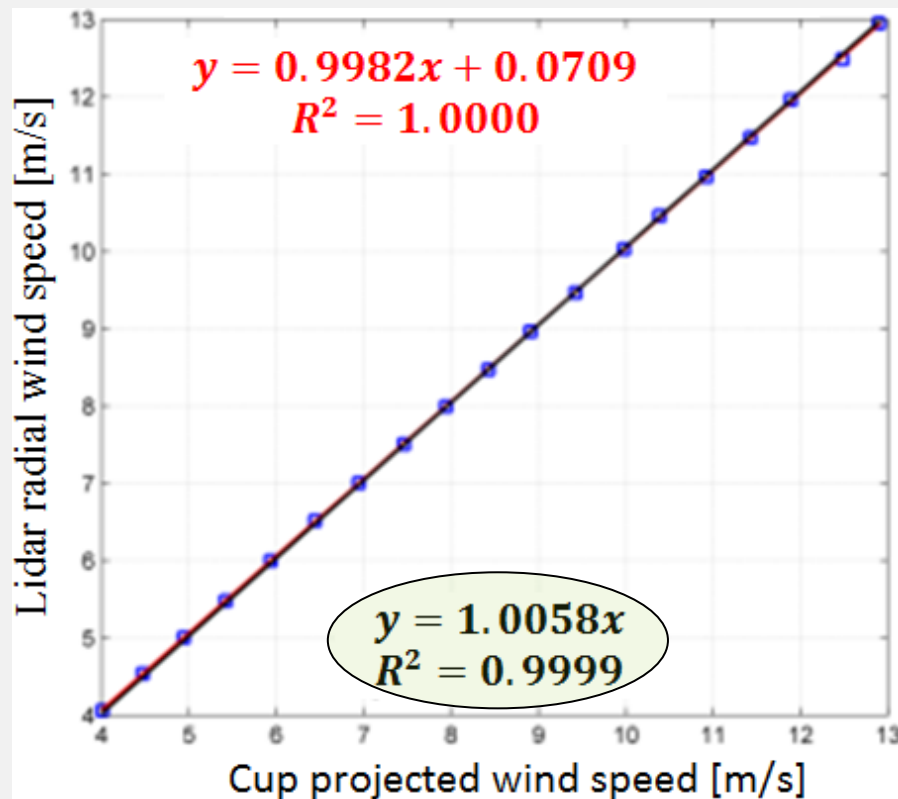
- Good agreement between lidars' RWS and the projection of the HWS on the LOS
- Influence of the WS distribution → use binned data instead



Calibration results (Avent: L, Zephyr: R)

- "binned" calibration results

- Use the forced regression
→ consistent gains
- Offset is not physical



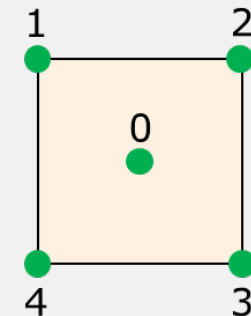
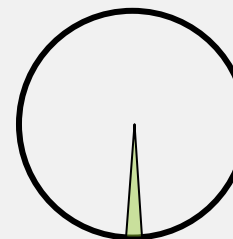
Calibration results

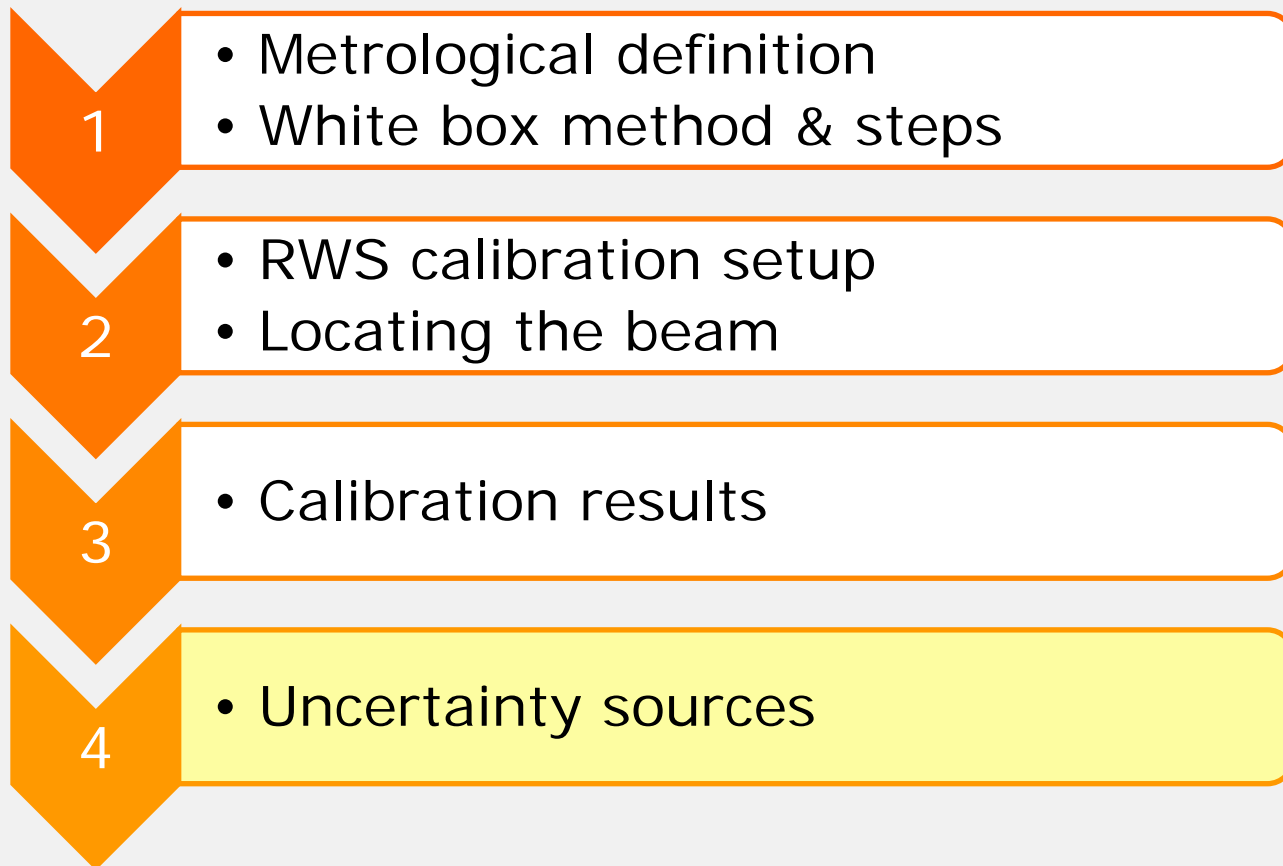
all 5 beams Demonstrator + ZDM

LOS / azimuth sector [deg]	Range selected [m]	LOS dir [deg]	Valid data points	Binned calibration					range of valid bins [m/s]	
				"Free" regression			Forced regression			
				gain	offset	R2	gain	R2	min	max
0	262	286,03	742	0,9982	0,0709	1,0000	1,0058	0,9999	4	13
1	252	285,99	502	1,0043	0,0314	1,0000	1,0072	0,9999	3,5	15,5
2	252	285,99	1087	1,0056	0,0267	1,0000	1,0084	1,0000	3	13,5
3	252	286,06	446	1,0097	-0,0046	0,9999	1,0090	0,9999	3,5	10
4	252	285,99	1508	1,0069	-0,0142	1,0000	1,0056	1,0000	3,5	15
179-181	253	287,44	2140	1,0153	-0,1049	0,9999	1,0054	0,9998	4	15
175-185	253	287,49	2140	1,0157	-0,1032	0,9999	1,0059	0,9998	4	15

- **LOS direction**
→ consistent results for each lidar
- **Forced regressions on binned data**
→ gains error $\sim 0.5 - 0.9\%$

ZDM 5-beam Demonstrator





Uncertainty sources (Avent: L, Zephyr: R)

- **Analytical methods (GUM)**
- **Expressed for each wind speed bin**
- **Sources**
 - **Reference wind speed** (cup) → according to IEC 61400-12-1
 - Wind tunnel calib uncertainty (B)
 - Operational (B)
 - Mounting (B)
 - **Relative wind direction**: sonic WD – LOS direction
 - Sonic calibration in wind tunnel (B)
 - LOS direction estimation (B)
 - **Position of the beam**: accurately known to be close to cup
 - Physical beam inclination (inclinometers calib) for the projection (B)
 - Beam height → $U_H = \alpha \cdot \Delta H / H \cdot V_{HWS} \approx 0.023\% \cdot V_{HWS}$ (B)
 - **Statistical uncertainty** in the RWS measurement characterising the dispersion of RWS measurements under "repeatable conditions" (A)
 - **TOTAL uncertainty**: $U_{RWS} = \sqrt{\sum U_i^2}$

Conclusion - further work

• Conclusions

- White box method applicable to both pulsed / CW nacelle lidars
 - **generic**
 - potentially for all lidars irrespective of their application
 - repeatable
- RWS calibration
- Limitations
 - Need for better cup anemometer calibration (uncertainty is predominant)
 - High TI at low height → not ideal measurement setup, but still yielding good results

• Further work

- Uncertainty derivation of parameters using custom reconstruction algorithms
- Sensitivity analysis (variability of calibration results)
 - Amount of valid points
 - Atmospheric conditions: T° , TI, thermal stability

Thanks for your attention!

QUESTIONS?

More info:

- website www.unitte.dk
- contact borr@dtu.dk



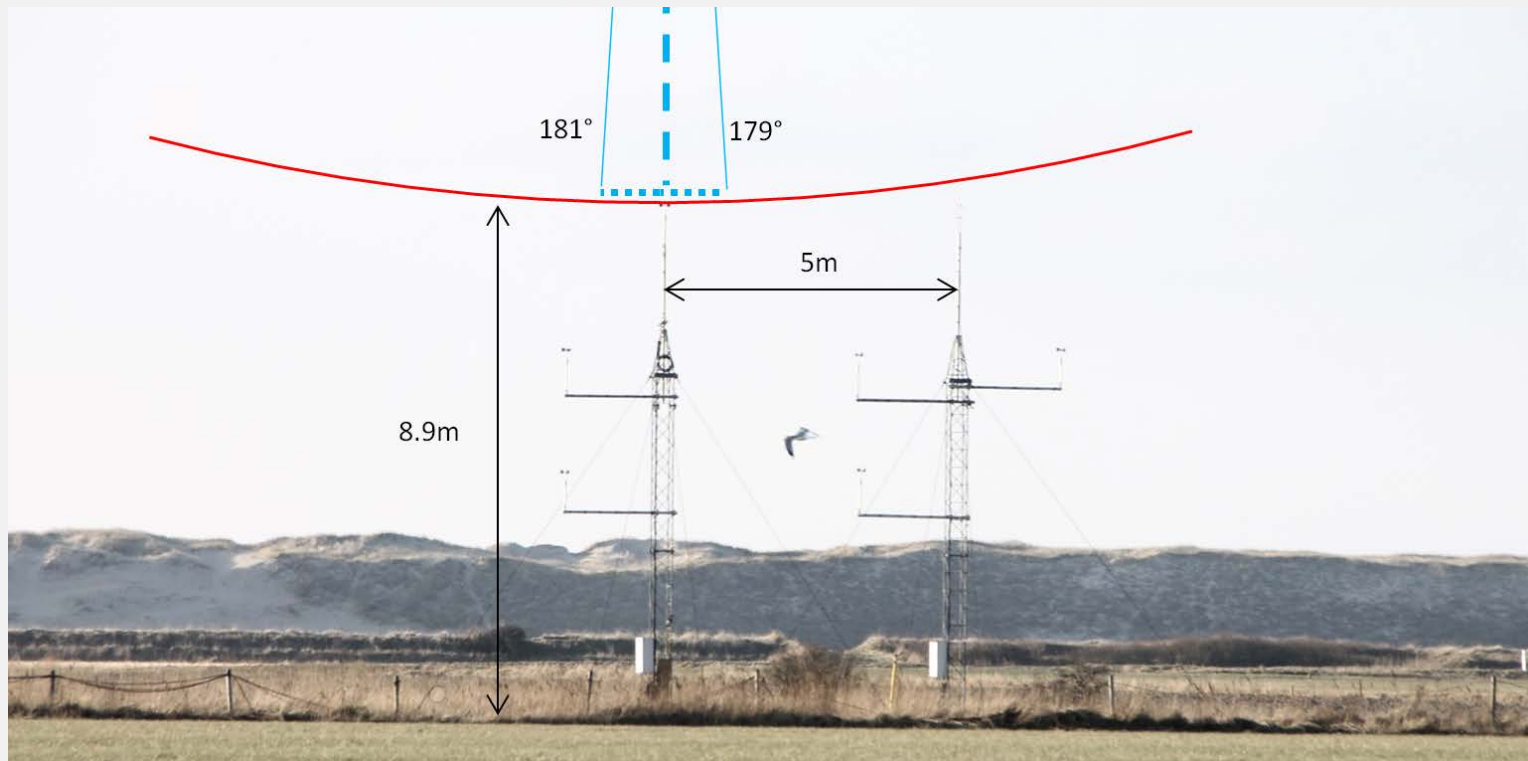
Preparing questions



Calibration results

ZDM

- Parameter to adjust: width of valid azimuth sector



- Used for averaging realtime data from "RAW" files
- Only one beam to calibrate since scanning: here "2-deg wide" sector
- NB: the selected arc is $\sim 20\text{m}$ large \rightarrow can influence results

Black & white box calibration of lidars

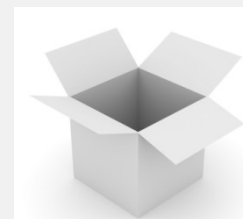
Two different principles

- **Lidar measurements and outputs**

- Measurand: frequency of the backscattered light
- Converts it in a Radial Wind Speed, i.e. the **component of the wind vector in the line of sight** (LOS, laser beam direction)
- RWS considered as the "raw measured quantity"
- Output parameters
 - obtained by applying mathematical models to a number of RWS measurements → reconstruction algorithms
 - Examples: HWS, shear, wind direction, veer, ...

- **Two principles**

- Black box: calibration of the "mathematically derived" parameter against the same type of parameter measured by a reference instrument
 - E.g. HWS vs. Cup anemometer wind speed
- White box: calibration of the parameters used as inputs to the reconstruction algorithm
 - individual beams RWS calib



Black & white box calibration of lidars

Black box: requirements, pros, cons, example (1/2)

- **Requirements**

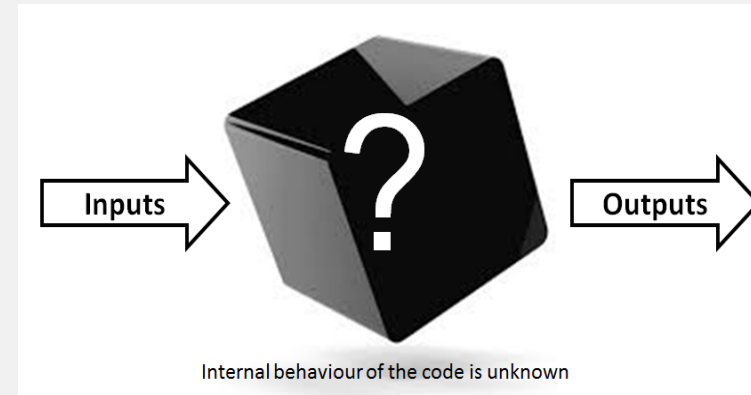
- availability / existence of a reference instrument for the type of data to calibrate
- reference instrument **MUST** be calibrated (certificate ...)

- **Pros**

- Direct comparison of the data:
 - reconstructed output vs. Reference
 - no additional algorithm to transform the data
 - fast and relatively easy

- **Cons**

- Need for multiple reference instruments: theoretically, one for each output
- Assumptions adding uncertainties
 - ➔ e.g. homogeneity, issue for nacelle-based lidars (horizontally shooting)
- **!!** the reconstructed output can physically not exist **!!**

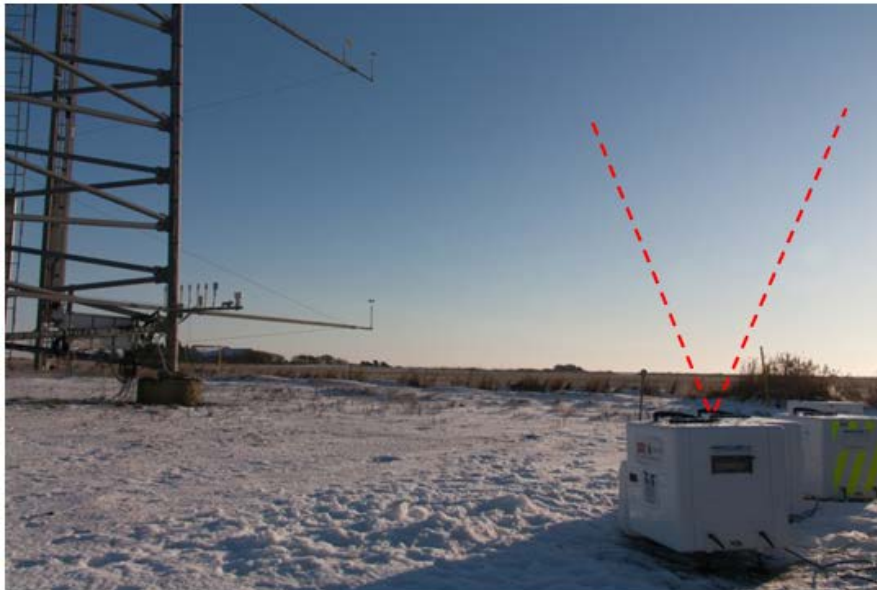


Black & white box calibration of lidars

Black box: requirements, pros, cons, example (2/2)

- **Example: calibration of ground-based profiling lidars**

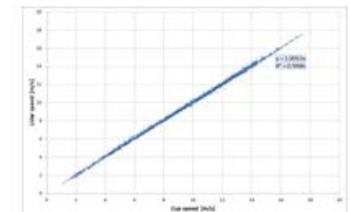
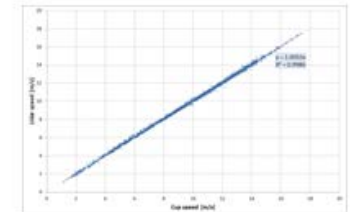
- Measurand: horizontal wind speed
- Reference: cup anemometers at several heights
- Additional uncertainties?
 - Measurement at same height?
 - Is the beam vertical? → inclinometer for roll angle
 - Homogeneity assumption is satisfied quite well



116m

...

40m



5 heights

Black & white box calibration of lidars

White box: requirements, pros, cons, example (1/2)

• Requirements

- ✓ – Being able to actually calibrate the RWS → availability / existence of reference instrument for wind speed and direction
- ✓ – Being able to check the geometry → e.g. angles used for HWS projection
- ✓ – Calibrate the inclinometers → roll and tilt
- ✗ – Having access to the mathematical model used by the manufacturer for reconstruction
- ?
- not the algorithms themselves
- Mandatory in order to derive uncertainties on the reconstructed outputs

• Pros

- Calibration of a physically existing quantity
- For nacelle lidars, homogeneity is not needed or less sensitive
- Uncertainties
 - on theoretically any reconstructed parameter
 - even for parameters that cannot be measured by reference instruments (shear?)

Black & white box calibration of lidars

White box: requirements, pros, cons, example (2/2)

- **Cons**

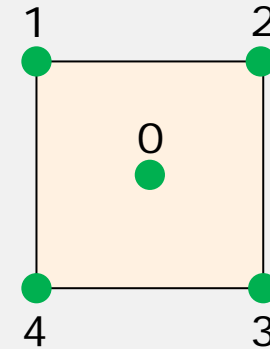
- Make sure that the reconstruction algorithm is correct
 - Does it get the physics right?
 - Suggestion 1: 3D flow simulation test cases
 - Suggestion 2: for each technology of lidar (different algorithm), at least two "black box" calib
- Longer duration
 - Calibration of successive LOS
 - ➔ 2-min average to fill the distribution quicker (not *5)
- Need for:
 - Inclinometers calibration
 - Geometry verification
 - RWS calibration

- **Example: calibration of nacelle-based lidars**

Calibration results

all 5 beams - Demonstrator

- **LOS 0 – LOS 4 – LOS 1 – LOS 0 – LOS 3 – LOS 2**



LOS	Range selected [m]	LOS dir [°]	Valid data points	Binned calibration					range of valid bins		TI range	T abs 2m range
				"Free" regression			Forced regression		[m/s]			
				gain	offset	R2	gain	R2	min	max		
0 (comb)	262	286,03	742	0,9982	0,0709	1,0000	1,0058	0,9999	4	13	10-17%	3-10° C
1	252	285,99	502	1,0043	0,0314	1,0000	1,0072	0,9999	3,5	15,5	10-16%	2-7° C
2	252	285,99	1087	1,0056	0,0267	1,0000	1,0084	1,0000	3	13,5	10-17%	4-8° C
3	252	286,06	446	1,0097	-0,0046	0,9999	1,0090	0,9999	3,5	10	9-16%	4-7.5° C
4	252	285,99	1508	1,0069	-0,0142	1,0000	1,0056	1,0000	3,5	15	10-18%	4-9° C

- **TI**
 - 10-17% ➔ relatively high because of measurement height (8.9m)
- **Temperature @2m**
 - Winter time in DK
 - No negative T in valid dataset!